CALIBRATION AND EVALUATION OF MULTICOMPONENT STRAIN-GAGE BALANCES

SUMMARY

This paper is a brief description of the methods used at Langley in calibrating and evaluating wind-tunnel strain-gage balances.

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Prepared for presentation to the NASA interlaboratory force measurements group meeting held at JPL on April 16 and 17, 1964

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INTRODUCTION

Of all the phases that a balance goes through in making it ready for tunnel testing use, the laboratory calibration and evaluation procedure is probably the most important. It is only through a complete and accurate calibration-evaluation process that the final performance and accuracy of a balance can be determined. At the same time the calibration-evaluation provides the design engineer with an invaluable source of information for assessing overall balance design characteristics.

In principle, the LRC calibration approach is based on the assumption that all possible first and second order interactions exist on a given balance until proven otherwise. In all, there are 26 first and second order interactions, plus one sensitivity constant, per component on a six-component balance which must be evaluated. These terms are listed as follows:

N	N^2					
A	NA	A^2				
m	Nm	Am	m^2			
ℓ	$N\ell$	$A\ell$	$m\ell$	ℓ^2		
n	Nn	An	mn	ℓn	n^2	
Y	NY	AY	mY	ℓY	nY	Y^2

The symbols used are:

N = normal force ℓ = rolling moment

A = axial force n = yawing moment

m = pitching moment Y = side force

In addition to the terms tabulated above, the calibration results will actually indicate all third order interactions except triple product terms such as $N \times A \times m$, $N \times \ell \times m$, etc. However, if these terms did exist they would be indicated in the final multicomponent proof loading.

Briefly, the necessity for seeking all possible interactions is based on the following:

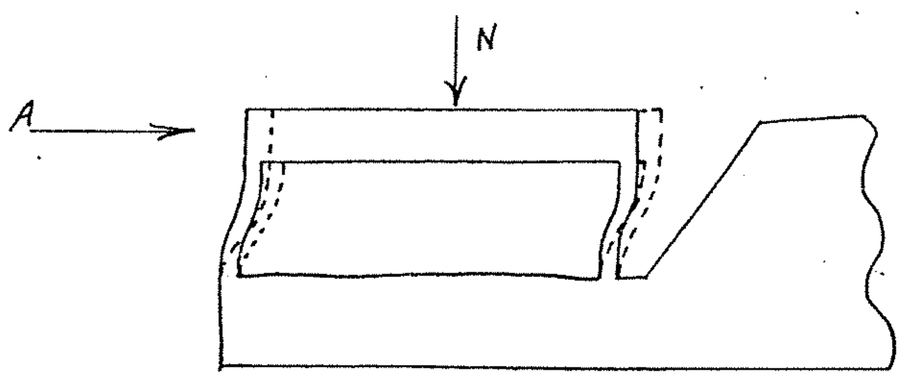
1. Most balances at LRC are designed to meet specific test requirements. Consequently, there is a wide variation in balance configurations in which characteristics can vary considerably. In order to fully assess balance performance it is mandatory that

each balance be completely evaluated. This is particularly true on high load to size ratio balances where high local stresses and deflections can cause sizeable interaction terms.

2. Performing a complete calibration on each balance permits its general and unrestricted use for any combination of loads within the calibration range.

3. Data gathered over the years substantiates the existence and frequency of occurrence of all interaction terms. This data, which was compiled for three basic balance configurations, is presented on pages 12, 13 and 14. The number of times a given interaction occurred on the balances considered is indicated by the "density" of the plotted points.

As stated previously, both first and second order interactions must be considered in balance evaluation. The first order terms result from such things as machining errors, gage location, and variations in gage factor. The second order terms are attributed to deflections - except the linear normal and pitch terms on axial force which are also caused by deflection. An example of a second order interaction caused by deflection is the (N x A) term which commonly occurs on the axial force component. The figure below illustrates the deflection of a simple axial measuring section under applied axial load.



If normal force is now applied to the section it is obvious that the axial beams, which behave like eccentric columns, will deflect an additional amount as indicated by the dotted lines. This added deflection will result in an additional electrical signal which is proportional to the (N x A) product. The (m x A) interaction can be explained in a similar manner.

In many cases it is possible to minimize or even eliminate some of the linear interactions. This can be accomplished by:

1. Carefully matching gages
2. Precise machining
3. Electrically "bleeding" out interactions

Second order terms can be minimized by designing for low deflections. However, the fact remains that a balance must deflect under load; therefore, some second order interactions will certainly exist. The balance shown on page 15 illustrates a case where test requirements dictated an unusual balance configuration. This type of balance, because of its length and separation of measuring elements, would certainly have sizeable second order interaction terms.

CALIBRATION PROCEDURE

On a six-component balance each bridge indicator reading, as a consequence of interactions, is a function of all six load components. The output of the normal force component, for example, can be expressed as a polynomial of the form:

$$\theta_N = k_N N + k_{N^2} N^2 + k_A A + k_{A^2} A^2 + k_{NA} NA + k_m m + k_{m^2} m^2 + k_{Nm} Nm \; . \; . \; . \; k_{Y^2} Y^2$$

There will be six equations of this type, one for each component, where N, A, m, etc. are the applied loads, k_N, k_{N^2}, etc. are the interaction coefficients, and the θ_N is the meter reading.

The equation as shown above is not particularly convenient for wind-tunnel use. Noting that $1/k_N$ is the normal force sensitivity constant it is possible to "normalize" the equation by multiplying both sides by this factor and putting in the form:

$$K_N \theta_N = N + K_{N^2} N^2 + K_A A + K_{A^2} A^2 + K_{NA} NA + K_m m + K_{m^2} m^2 \; . \; . \; . \; +$$

$$K_{Nm} Nm \; . \; . \; . \; + K_{Y^2} Y^2$$

In this expression (K_N) is the normal force sensitivity constant, θ_N is the normal force meter reading and K_{N^2}, K_A, etc. are the "normalized" interaction coefficients. In this form the coefficients are independent of the readout system used.

The equation can now be put in a more convenient form by rearranging and solving for (N).

$$N = K_N\theta_N - \left\{K_{N^2}N^2 + K_A A \ . \ . \ . \ K_{Y^2}Y^2\right\}$$

$$N = K_N\theta_N - \left\{\Sigma \text{ (interactions)}\right\}$$

In general there will be six such equations, one for each component. The purpose of the calibration-evaluation procedure is to determine these expressions.

In outlining the LRC calibration procedure the following points will be considered: calibration equipment, loading system for evaluating specific interactions, data plotting, interaction equation derivation, proof loading, and data reduction.

Calibration Equipment and Setup

The figure on page 16 illustrates a typical calibration fixture and "long arm" arrangement used in calibrating internal sting-supported balances. The fixture is an accurately machined box, fitted to the balance exactly as the model would be, with precisely located V-shaped grooves in which the loads are applied during calibration. Loads are applied using suitable weight hangers which are fitted with the double knife edge arrangement illustrated on page 16. The use of double knife edges permits accurate load location and also eliminates transmission of unwanted moments to the fixture. The long arms, which are accurately located on the fixture, provide a means for loading the moments on the balance. By transferring a small weight from the moment center location to the ends of these arms, it is possible to apply virtually pure moments. During calibration the balance is sting-mounted in a rig (see pages 17 and 18) which has provision for releveling in the roll and pitch planes.

Loading, Plotting and Interaction Evaluation

The loading procedure used at LRC is designed to systematically evaluate the interaction terms indicated on page 1. The loads applied to the balance during calibration are defined as primary or secondary. Primary loads are applied one at a time, in increments, and are intended to load one component at a time. Secondary loads, which are held constant during calibration, are applied in conjunction with primary loads. The weights used in calibration are cast iron or brass discs which are frequently checked to insure 0.1 percent accuracy. In applying loads normal to the gravity axis the knife edge bellcrank illustrated on page 19 is used. These units eliminate the friction problems normally encountered in "V" groove pulley systems. Precision levels are used for repositioning the balance throughout the loading procedure. The loading sequence includes application and removal of loads in three to five increments, releveling at each step, and recording the output meter readings.

To illustrate the manner in which balance interactions are obtained, a number of specific examples will be considered in detail. The graphs on pages 20, 21 and 22 illustrate the manner in which the normal force output data, on a six-component balance, is plotted. Similar plots are made for the remaining five components. Page 23 is a typical work sheet used in calculating the "normalized" interaction coefficients.

Determination of the K_N and K_{N2} Terms

Normal force, both positive and negative, is applied in increments at the balance moment center. (The moment center is fixed during design and serves as a reference point on the balance about which moments are measured.) During this loading sequence the balance is releveled at each load increment and all meter readings recorded and plotted. The top plot on page 20 shows the output of the normal force component as a function of applied load. Visual inspection of the curve provides a quick check on the performance of the balance as a function of applied load. Hysteresis, zero shift, and scatter can be detected with relative ease. The determination of the count value of the interaction can also be found simply by inspection. The count values of the first and second order terms are obtained directly from the end point of the curve as follows:

$$\theta_N = \frac{(1060) - (-1040)}{2} = +1050 \text{ counts}$$

This is the sensitivity (in counts) of the normal component

$$\theta_{N2} = \frac{(1060) + (-1040)}{2} = +10 \text{ counts}$$

These figures are entered on the worksheet shown on page 23. Subsequent routine calculations, indicated at the top of each column, result in interactions in normalized form.

Determination of K_m and K_{m^2} Terms

A small normal force, usually 10 percent of full normal force, is applied at the balance moment center and the readout indicators reset to zero. This load is now transferred in increments to and from the end of the forward (+x) arm and then the aft arm (-x position). The balance-fixture assembly is turned over and the above procedure is repeated with the opposite sign of normal force. The results of the four loadings are plotted (in red) versus pitching moment as indicated on the center plot of page 20. The first and second order terms can, in this case, also be obtained directly from the end points.

$$K_m = \frac{(+21) - (-9)}{2} = +15 \text{ counts}$$

$$K_{m^2} = \frac{(+21) + (-9)}{2} = +6 \text{ counts}$$

These figures are entered on the worksheet (page 23) and through subsequent calculation reduced to normalized interaction form.

Determination of the K_{Nm} Term

Full normal force is applied at the moment center and the meters reset to zero. Ten percent of this load is transferred, in increments, to the forward arm and aft arms and the data recorded. The balance is turned over and the loading repeated with the opposite sign of normal force. The resulting data is shown on the center plot (blue points) of page 20. A direct comparison between the blue and red points (pure pitch) will yield a count value which is directly proportional to the (N x m) product. In order that this be a "perfect" interaction the deviation of the blue points relative to the red should be the same at each load point. The sign of the interaction is found by considering the signs of the applied loads at a given point, and the relative position of the point with respect to the red "base" point. For the blue triangle on the right of the plot there exist:

(a) Positive pitch
(b) Positive normal force
(c) Direction of deflection relative to red point - positive

which yields [(+)(+)(+) = +], therefore a positive interaction. For this case the (N x m) interaction is

$$K_{Nm} = +5 \text{ counts}$$

Determination of the (m x ℓ) Interaction

The procedure here is similar to the one used for the (K_{Nm}) determination except that rolling moment is now the auxiliary load. The roll auxiliary load is generated by placing approximately 10 percent of rated normal force at the ends of the roll arms and rezeroing the meters. Pitch is applied in the conventional manner. The balance is then turned over and the procedure repeated with the opposite sign of normal force. The results of this loading are plotted versus pitching moment and are indicated by the purple and green points on the middle plot of page 20. The value of the ($K_{m\ell}$) term is obtained by inspection by comparing the spread relative to the red base points. The count value is found to be:

$$K_{m\ell} = +10 \text{ counts}$$

Determination of the K_ℓ, $K_{\ell 2}$ and $K_{N\ell}$ Terms

The procedure is similar to the method used for finding the K_m, K_{m2} and K_{Nm} terms. The resulting plots of these loadings are shown on page 20. The interactions derived from these curves are:

$$K_\ell = -13 \text{ counts}$$

$$K_{\ell 2} = 0$$

$$K_{N\ell} = +8 \text{ counts}$$

Determination of the K_{NA} Term

Full positive axial force is applied to the balance (over a "pulley") and the meters rezeroed. Both positive and negative normal forces are loaded in increments and the data recorded. The resulting data (on normal force) is shown plotted (yellow points) on page 21. The (K_{NA}) term is obtained by comparing this curve directly with the pure normal force loading shown at the top of page 20. The magnitude and sign of the interaction is

$$K_{NA} = +5 \text{ counts}$$

The sign of the interaction here is again determined from the signs of the loads acting and direction which the yellow point moved relative to the "base" point. In this case (considering the right side of the curve):

(+ Normal)(+ Axial)(+ Direction) = Positive interaction

Determination of the K_{NY} Term

Positive side force is applied (over a "pulley") to the balance, the meters zeroed out, positive and negative normal force applied in increments, and the data recorded and plotted (blue points) as indicated on the top plot of page 21. Applying the same procedure used in the K_{NA} determination the interaction is found to be

$$K_{NS} = -7 \text{ counts}$$

Determination of the K_{Nn} Term

Full yawing moment is applied by moving side force (applied over a "pulley") 2.5 inches off the moment center. The meters are rezeroed and positive and negative normal force applied as before. The resulting data is plotted (green points) at the top of page 21. Since full side force is also present during this loading it is necessary to compare back to the normal x side loading rather than the pure normal loadings to determine the interaction. In this case the interaction is found to be

$$K_{Nn} = -3 \text{ counts}$$

The remaining interactions can be derived using the exact methods outlined in the above examples. These interactions have been evaluated and are tabulated on the worksheet on page 23. The loading schedule used at LRC for balance evaluation is outlined on page 24.

Proof Loading

The final step in the evaluation procedure consists of proof loading the balance to verify the accuracy of the derived interactions. The proof loading consists of approximately 100 different combinations of full and half loads which are applied to the balance in predetermined manner. Using the derived interaction equations, the forces and moments are then calculated and compared with the applied proof loads. If errors are detected their cause can quickly be pinpointed and corrective measures taken to eliminate them. In any event it is the final proof loading that determines final balance accuracy. After the balance interactions have been verified they are published in the standard form shown on pages 25 and 26.

Data Reduction

Conversion of raw wind-tunnel data into the forces and moments acting on the model involves solution of the interaction equations using an iteration process. As indicated previously, the interaction equation for a six-component balance can be written:

$$N = K_N\theta_N - \Sigma \text{ (interactions on normal)}$$

$$A = K_A\theta_A - \Sigma \text{ (interactions on axial)}$$

. . . . .

. . . . .

. . . . .

$$Y = K_Y\theta_Y - \Sigma \text{ (interactions on side)}$$

From the raw tunnel data it is first necessary to compute the "uncorrected" forces and moments. These are:

$$N_1 = K_N\theta_N$$

$$A_1 = K_A\theta_A$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$Y_1 = K_Y\theta_Y$$

These values are now substituted into the interaction equations to give

$$N_2 = N_1 - \Sigma\ (\text{interactions})_1$$

$$A_2 = A_1 - \Sigma\ (\text{interactions})_1$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$Y_2 = Y_1 - \Sigma\ (\text{interactions})_1$$

The quantities N_2, A_2 . . . Y_2 are the partially corrected forces and moments.

Substituting these "more correct" values back into the general relations yields:

$$N_3 = N_1 - \Sigma\ (\text{interactions})_2$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$Y_3 = Y_1 - \Sigma\ (\text{interactions})_2$$

The nth values of the corrected forces and moment are

$$N_n = N_1 - \Sigma\ (\text{interactions})_{n-1}$$

$$\cdots\cdots$$

$$\cdots\cdots$$

$$\cdots\cdots$$

$$Y_n = Y_1 - \Sigma\ (\text{interactions})_{n-1}$$

In general the procedure is continued until the difference between the successive iterations fall within a given or specified limit. When interactions are small two or three cycles will yield accurate results. However, when large interactions exist as many as eight iterations may be required.

JFGuarino.mle
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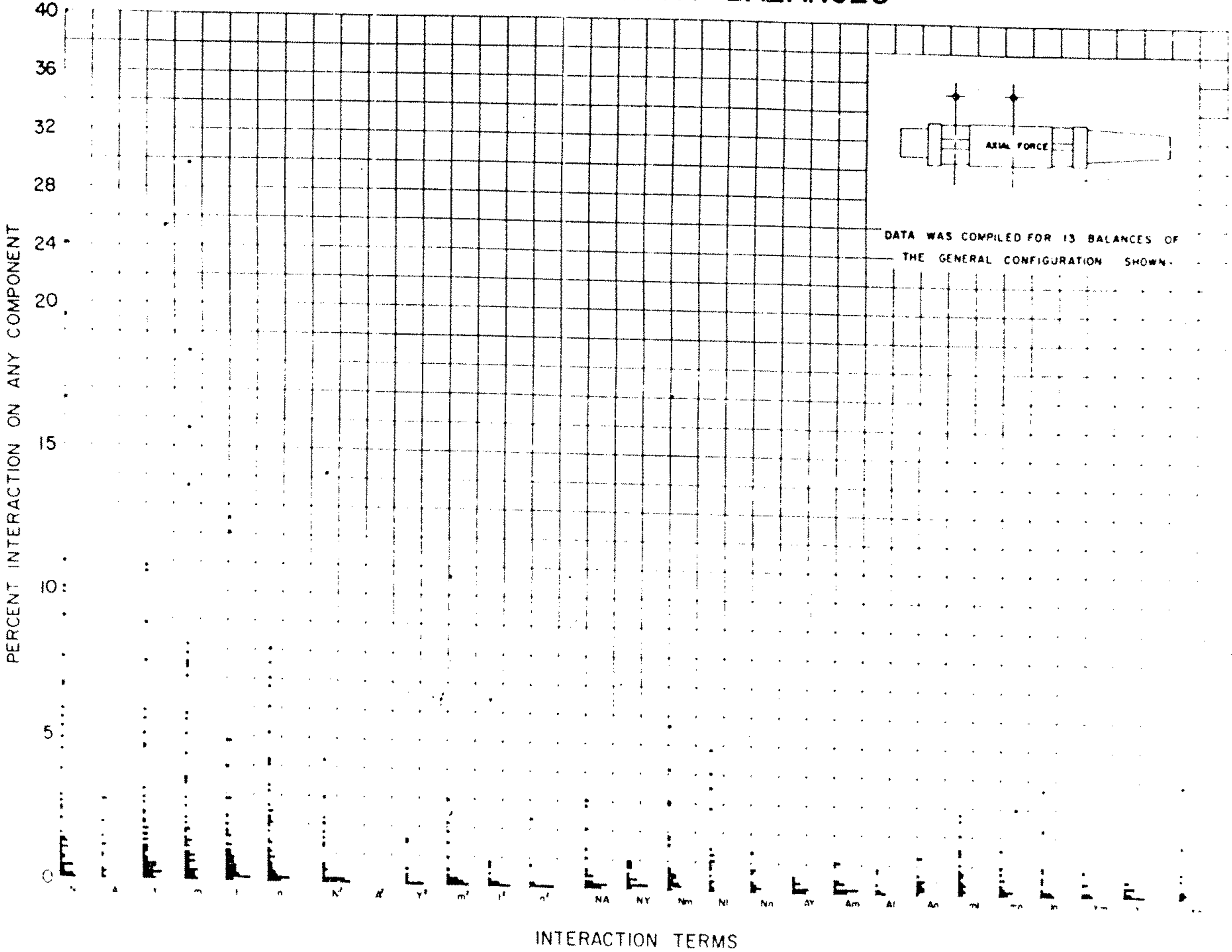
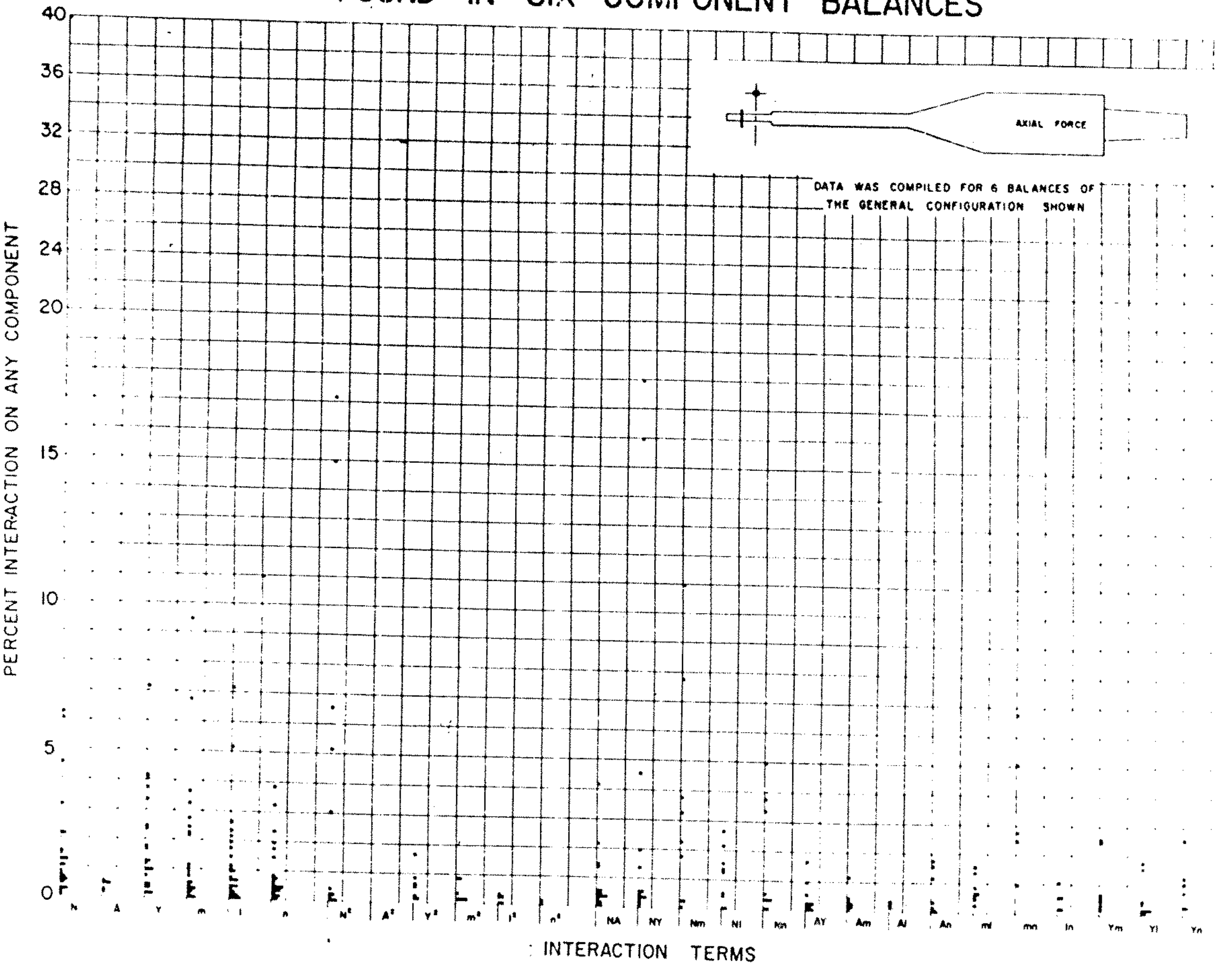
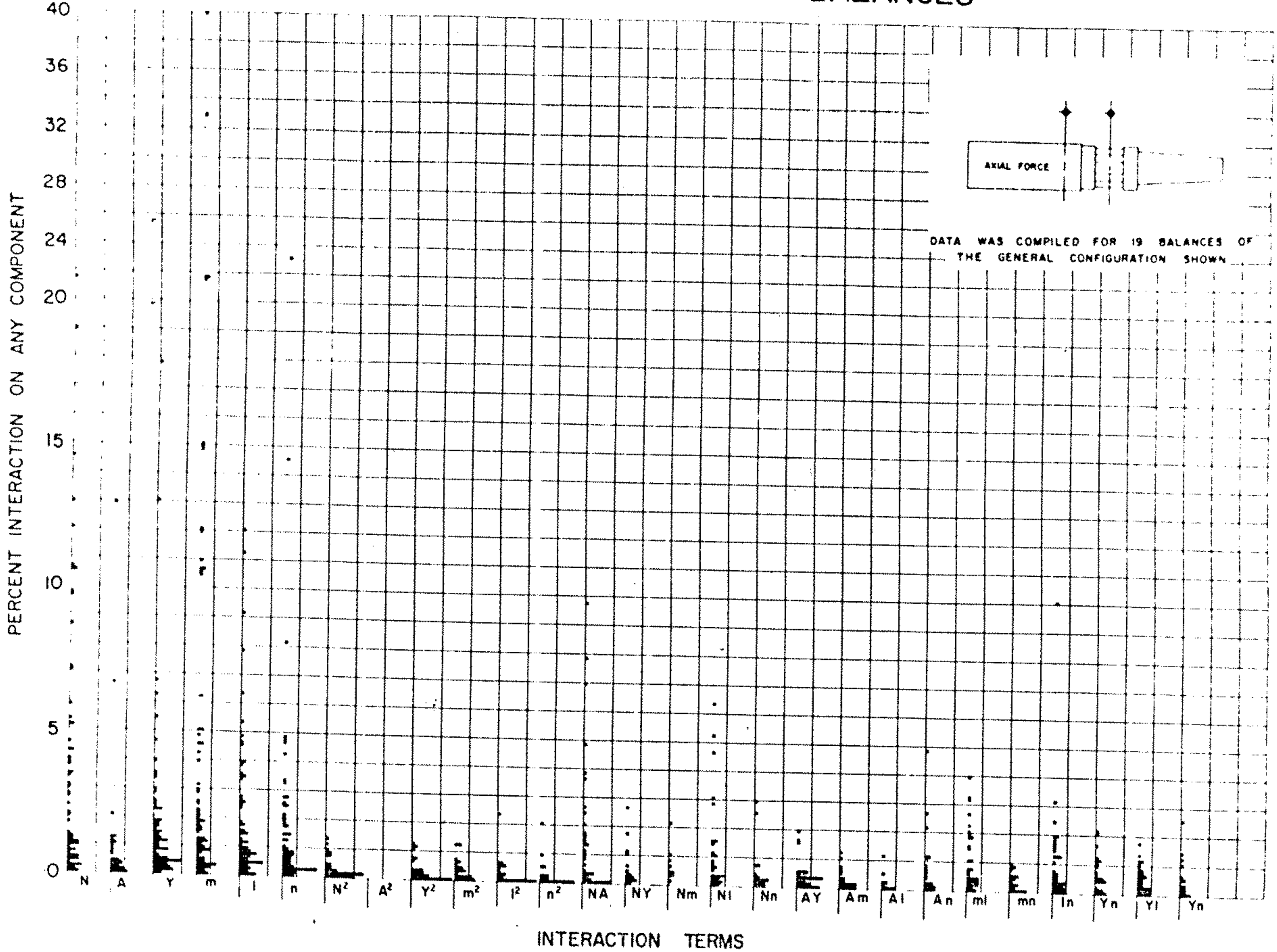
TABULATION OF INTERACTION TERMS FOUND IN SIX COMPONENT BALANCES

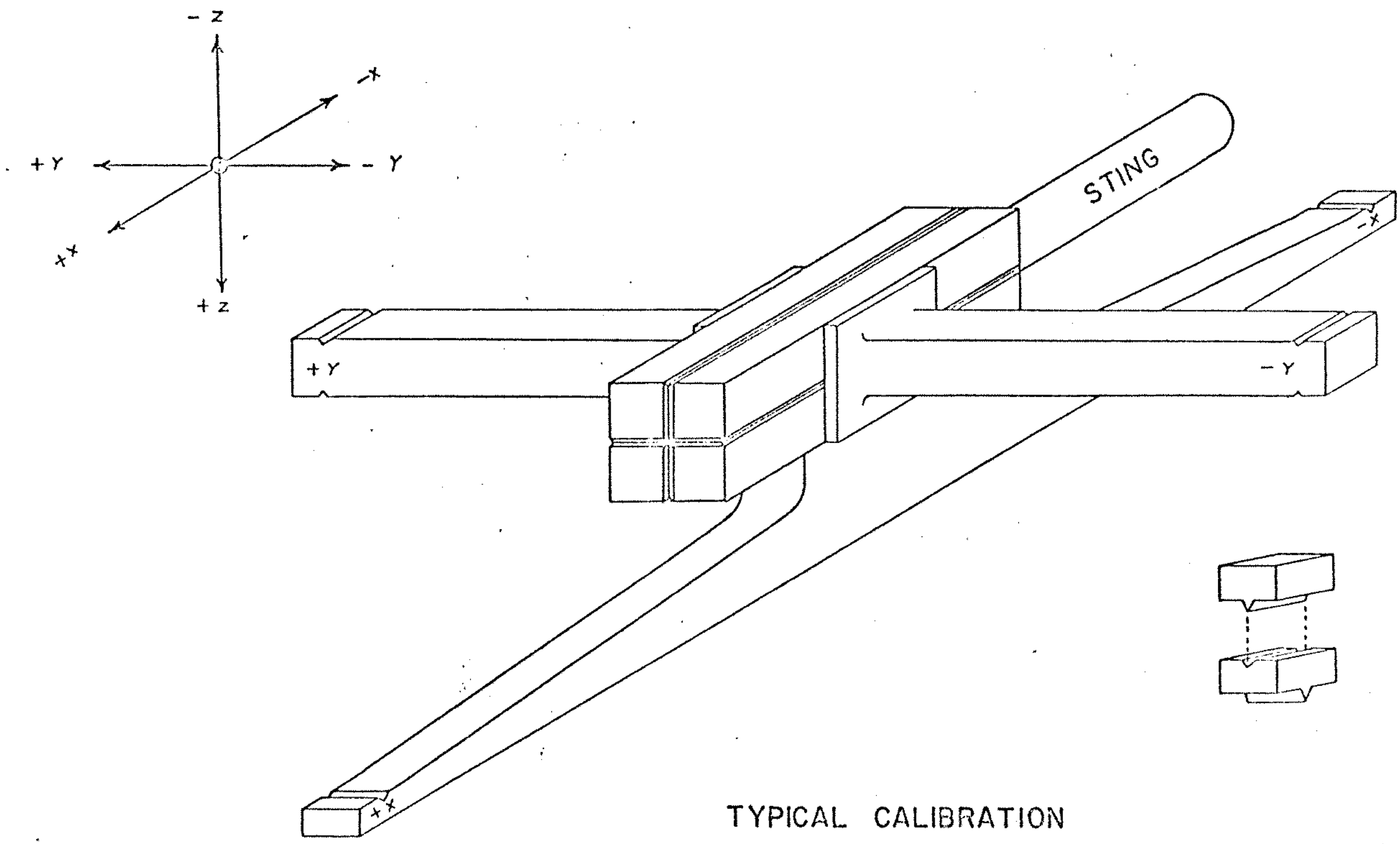


TABULATION OF INTERACTION TERMS FOUND IN SIX COMPONENT BALANCES

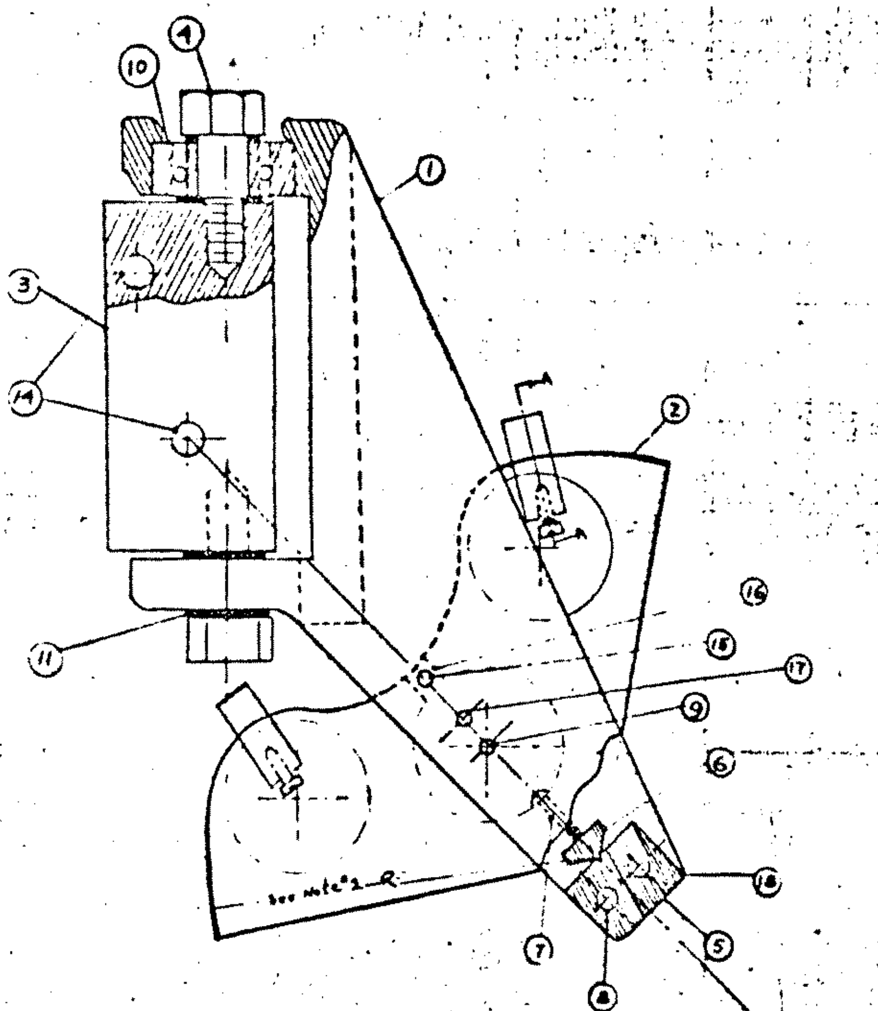


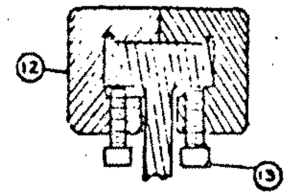
TABULATION OF INTERACTION TERMS FOUND IN SIX COMPONENT BALANCES





TYPICAL CALIBRATION
BODY & ARMS





Section A-A

NOTE:
1 Distance from end of Knife edge to ends Of crank must be kept equal within ±.003 inches

FILE
APR 10 1963

No	Description	Reqd	Material
1	Arm	1	Steel
2	CRANK	1	Dural
3	Block	1	Steel
4	See detail sheet	2	"
5	Support block	1	"
6	Knife edge	1	"
7	4-48 -3/4 screws	2	"
8	Stock #206281 3/16 x 2 Aircraft	2	"
9	5-86 - 2 Aircraft	2	"
10	Wheel bearing New Departure(7401)	2	"
11	Washer		"
12	Clamp	4	"
13	#10-32 5/8	4	"
14	5/16 - 24NF x 1 7/8 AN Bolt & Nut	2	"
15	Stock no. 205287 Aircraft	2	"
16	1/32 Thick Brass Clamp	1	Brass
17	#10-32 -1	2	Steel
18	Spacer	2	"

DATE	LET.	REVISION	BY

NEXT ASSEMBLY | UNIT OR PROJECT | SCALE: None

MATERIAL: As Noted | HEAT TREAT

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
LANGLEY AIR FORCE BASE, VA.

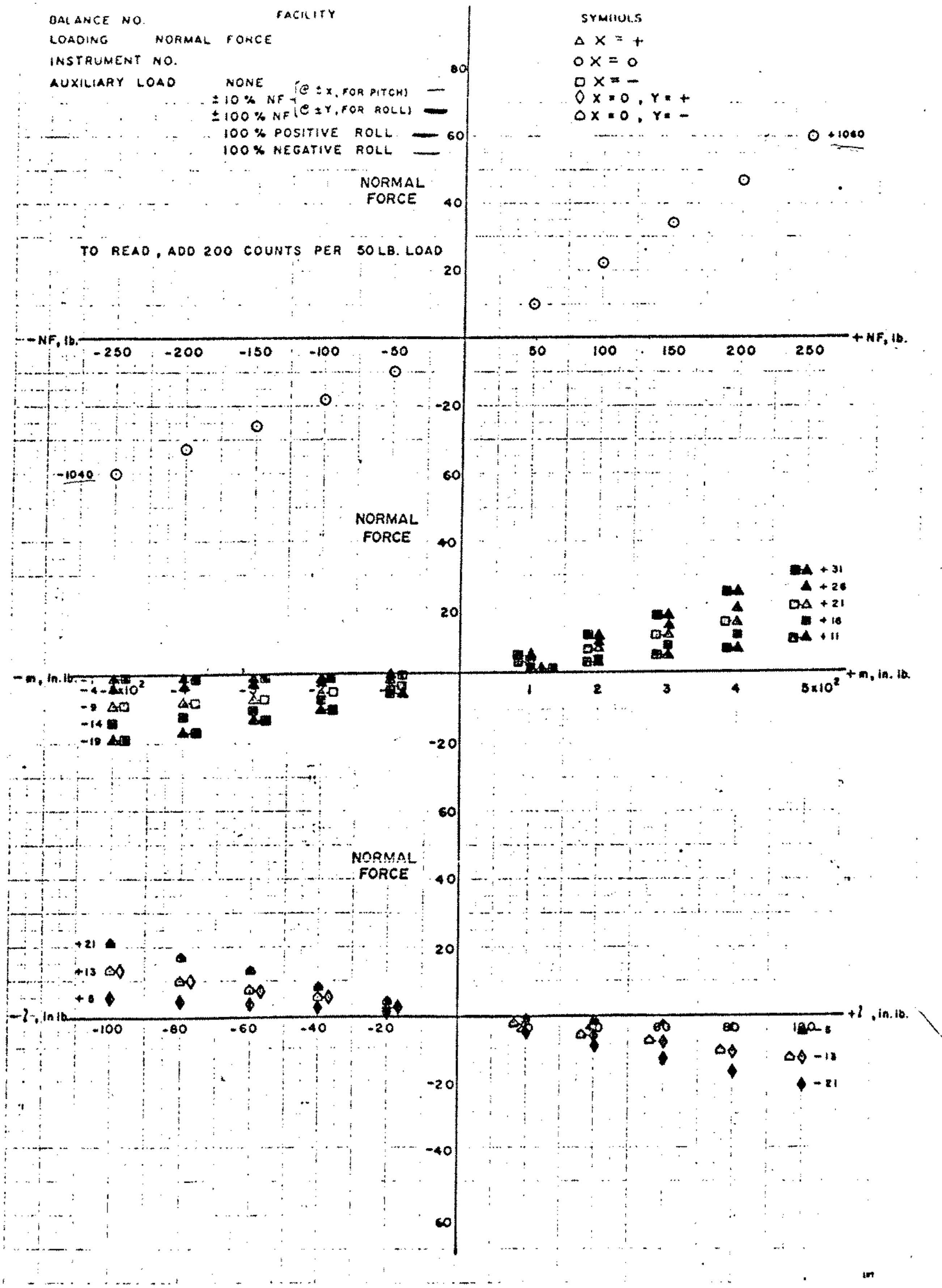
TOLERANCE ON DIMENSIONS UNLESS SHOWN OTHERWISE: ANGULAR ±

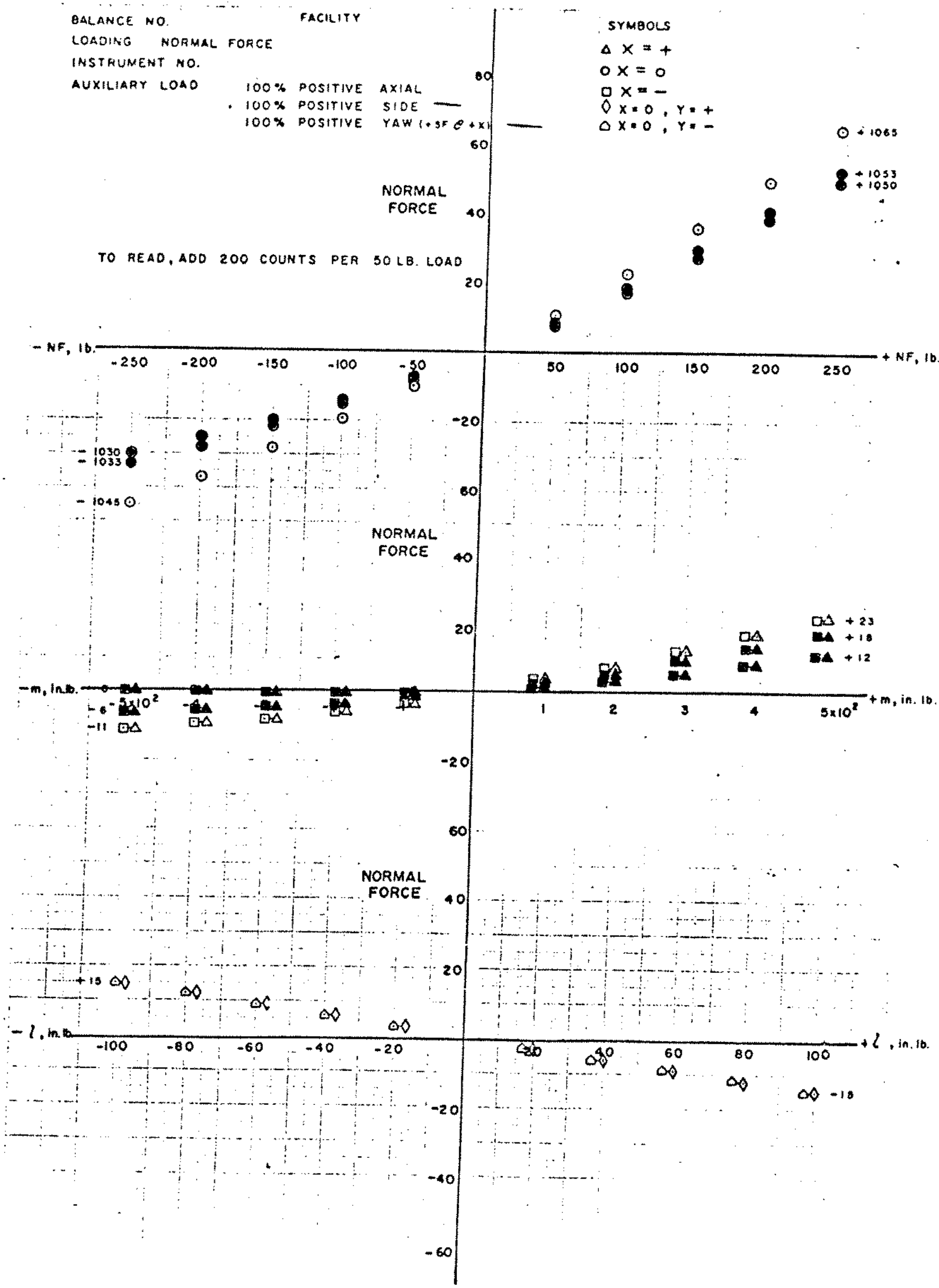
SURFACE FINISH IN MICROINCHES RMS UNLESS SHOWN OTHERWISE

EST. FIN WEIGHT

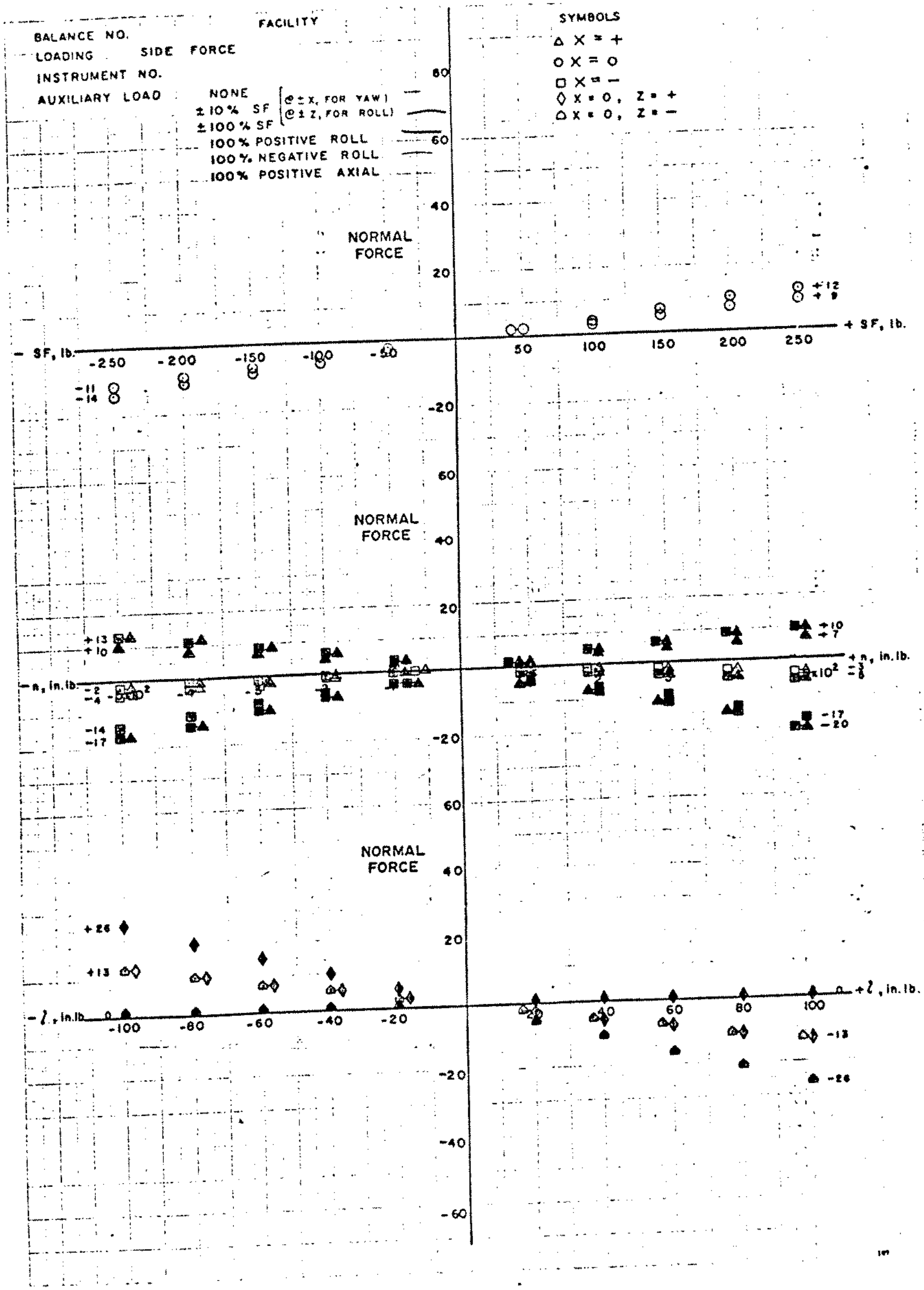
Bell Crank Assembly

LC 708591


BALANCE NO.
FACILITY
LOADING NORMAL FORCE
INSTRUMENT NO.
AUXILIARY LOAD NONE
±10% NF (@ ±X, FOR PITCH)
±100% NF (@ ±Y, FOR ROLL)
100% POSITIVE ROLL
100% NEGATIVE ROLL
SYMBOLS
Δ X = +
○ X = 0
□ X = −
◇ X = 0 , Y = +
△ X = 0 , Y = −
NORMAL FORCE
TO READ, ADD 200 COUNTS PER 50 LB. LOAD
+1060
−1040
− NF, lb.
+ NF, lb.
−250
−200
−150
−100
−50
50
100
150
200
250
80
60
40
20
−20
NORMAL FORCE
− m, in. lb.
+ m, in. lb.
−4
x10²
−9
−14
−19
1
2
3
4
5x10²
+31
+26
+21
+16
+11
NORMAL FORCE
− l, in. lb.
+ l, in. lb.
−100
−80
−60
−40
−20
60
80
100
+21
+13
+5
−5
−13
−21
−40
60



BALANCE NO.
FACILITY
LOADING NORMAL FORCE
INSTRUMENT NO.
AUXILIARY LOAD
100% POSITIVE AXIAL
100% POSITIVE SIDE
100% POSITIVE YAW
SYMBOLS
NORMAL FORCE
TO READ, ADD 200 COUNTS PER 50 LB. LOAD
- NF, lb.
+ NF, lb.
-m, in.lb.
+m, in. lb.
5x10²
- l, in.lb.
+ l, in. lb.


FACILITY
BALANCE NO.
LOADING SIDE FORCE
INSTRUMENT NO.
AUXILIARY LOAD
NONE
± 10 % SF (@ ± X, FOR YAW)
± 100 % SF (@ ± Z, FOR ROLL)
100 % POSITIVE ROLL
100 % NEGATIVE ROLL
100 % POSITIVE AXIAL
SYMBOLS
△ X = +
○ X = 0
□ X = −
◇ X = 0, Z = +
⌂ X = 0, Z = −
NORMAL FORCE
+ SF, lb.
− SF, lb.
+ n, in. lb.
− n, in. lb.
+ l, in. lb.
− l, in. lb.
NORMAL FORCE
NORMAL FORCE

BALANCE NO. __________________
FACILITY: __________________

FORCE OR MOMENT: NORMAL 250#

SENSITIVITY CONSTANT .2381 #/count

(1) TERMS	(2) FORCE OR MOMENT # OR "#	(3) COUNT VALUE OF TERMS	(4) % of F. S. (3) x 100	(5) (3)/(2)	(6) (5) x sen. constant	(7) (6)x(2) x 100 / # or "#
N	250	1050	—	—	—	—
A						
m	500	+15	1.4	+.03000	+.00 7142	1.4
l	100	-13	1.2	-.1300	-.03095	1.2
n	500	-1.5	0.1	-.003000	-.000 7143	0.1
S	250	+10	1.0	+.04000	+.009524	1.0
N^2	(250)(250)	+10	1.0	+.000 1600	+.0000 3810	1.0
NA	(250)(40)	+5	0.5	+.000 5000	+.000 1191	0.5
Nm	(250)(500)	+5	0.5	+.0000 4000	+.00000 9524	0.5
Nl	(250)(100)	+8	0.8	+.000 3200	+.0000 7619	0.8
Nn	(250)(500)	-3	0.3	-.0000 2400	-.00000 5714	0.3
NS	(250)(250)	-7	0.7	-.000 1120	-.0000 2667	0.7
A^2						
Am	(40)(500)	+2	0.2	+.0001000	+.0000 2381	0.2
Al	(40)(100)	-2	0.2	-.0005000	-.000 1190	0.2
An	(40)(500)	+2	0.2	+.0001000	+.0000 2381	0.2
AS	(40)(250)	+3	0.3	+.000 3000	+.0000 7143	0.3
m^2	(500)(500)	+6	0.6	+.0000 2400	+.00000 5714	0.6
ml	(500)(100)	+10	1.0	+.000 2000	+.0000 4762	1.0
mn	(500)(500)	-6	0.6	-.0000 2400	-.00000 5714	0.6
mS	(500)(250)	-3	0.3	-.0000 2400	-.00000 5714	0.6
l^2						
ln	(100)(500)	+15	1.4	+.000 3000	+.0000 7143	1.4
lS	(100)(250)	-13	1.2	-.000 5200	-.000 1238	1.2
n^2	(500)(500)	-3.5	0.3	-.0000 1400	-.00000 3333	0.3
nS	(500)(250)	+12	1.1	+.0000 9600	+.0000 2286	1.1
S^2	(250)(250)	-1	0.1	-.0000 1600	-.00000 3810	0.1

NASA-Langley, 1961

TABLE I.- LOADING SCHEDULE

Term being evaluated	Primary load added (5 increments)	Secondary load added (constant)	Number of loading setups
A, A^2	$+A$	None	1
S, S^2	$\pm S$	None	2
n, n^2	$\pm n$	$\pm\frac{S}{10}$	4
N, N^2	$\pm N$	None	2
m, m^2	$\pm m$	$\pm\frac{N}{10}$	4
l, l^2	$\pm l$	$\pm\frac{N}{10}$	4
mN	$\pm m$	$\pm N$	4
lN	$\pm l$	$\pm N$	4
ml	$\pm m$	$\pm l$, $\pm\frac{N}{10}$ $(2)^{\dagger}$	8
NA	$\pm N$	$+A^*$	2
mA	$\pm m$	$+A^*$, $\pm\frac{N}{10}$	4
lA	$\pm l$	$+A^*$, $\pm\frac{N}{10}$	4
lS	$\pm l$	$\pm S$	4
nS	$\pm n$	$\pm S$	4
nl	$\pm n$	$\pm l$, $\pm\frac{S}{10}$ $(2)^{\dagger}$	8
SA	$\pm S$	$+A^*$	2
nA	$\pm n$	$+A^*$, $\pm\frac{S}{10}^*$	4
NS	$\pm N$	$+S^*$	2
mS	$\pm m$	$+S^*$, $\pm\frac{N}{10}$	4
Nn	$\pm N$	$+S^*$, $\pm n^*$	4
mn	$\pm m$	$+S^*$, $\pm n^*$, $\pm\frac{N}{10}$	8
27 total			83 total

*Loading utilizing a pulley.

†Two loads of $\frac{N}{10}$ or $\frac{S}{10}$ type.